A COMPARISON OF THE TIME VARIATION
OF RADIAL ABUNDANCE GRADIENTS
FROM PLANETARY NEBULAE AND OPEN CLUSTERS

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Abstract. The temporal behaviour of the radial abundance gradients has important consequences on models for the chemical evolution of the Galaxy. We present a comparison of the time variation of the abundance gradients in the Milky Way disk as determined from a sample of planetary nebulae and open clusters. We conclude that the [Fe/H] gradients as measured in open cluster stars strongly support the time flattening of the abundance gradient as recently determined from O/H measurements in planetary nebulae. We estimate the average flattening rate in the time interval 10 Myr $< \tau <$ 5 Gyr as roughly 0.005 dex kpc^{-1} Gyr^{-1}.

1. Introduction

It is now generally accepted that the radial abundance gradients observed in the Milky Way disk are among the main constraints of models for the chemical evolution of the Galaxy. The study of the gradients comprise the determination of their average magnitudes along the disk, which include possible space variations, and their time evolution during the lifetime of the Galaxy (see for example Henry & Worthey 1999, Maciel 2000 and Maciel & Costa 2003 for recent reviews).

The magnitudes of the gradients can be derived from a variety of objects, such as HII regions, early type stars, planetary nebulae, etc. Recent investigations include Deharveng et al. (2000), Andrievsky et al. (2002) and Maciel et al. (2003), for HII regions, cepheid variables and planetary nebulae, respectively. Average values are generally in the range −0.04 to −0.07 dex/kpc for the O/H gradient, with similar values for other element ratios when available, as in the case of cepheids and planetary nebulae.

The space variations of the gradients are more controversial. Some flattening at large galactocentric distances is clearly discernible in a sample of galactic planetary nebulae, as shown by Maciel & Quireza (1999) and more recently by Costa et al. (2004), on the basis of a study of nebulae located in the direction of the galactic anticentre. These results are supported by some work on HII regions (see for example Vílchez & Esteban 1996). The cepheid data are consistent with a flattened

1

gradient near the solar neighbourhood, as suggested by Andrievsky et al. (2002). On the other hand, apparently no flattening is observed in some recent studies of O, B stars in the galactic disk (see for example Smartt 2000).

Probably the most interesting property of the gradients is their time variation, as it appears to be a very distinctive constraint of many recent chemical evolution models (cf. Tosi 2003). As an example, models by Hou et al. (2000) and Alibs et al. (2001) predict a continuous time flattening of the gradients, while models by Chiappini et al. (2001) are consistent with some steepening in a timescale of 3 to 10 Gyr. Therefore, it is extremely important to produce observational constraints to the time evolution of the gradients, along with their magnitudes and possible space variations. Recently, Maciel et al. (2003) suggested that the O/H gradient is flattening from roughly -0.11 dex/kpc to -0.06 dex/kpc during the last 9 Gyr, or from -0.08 dex/kpc to -0.06 dex/kpc in the last 5 Gyr. These results were obtained using a large sample of planetary nebulae for which accurate abundances have been obtained, and for which the ages of the progenitor stars have been individually determined. As discussed by Maciel et al. (2003), the absolute ages derived are probably not accurate, but the relative ages of the stars are better determined, so that the time behaviour of the gradient can be derived, at least for the last 5 Gyr, which include most objects in the sample.

In this work, we compare the results obtained by Maciel et al. (2003) for the planetary nebulae with some recent and independent determinations based on open cluster stars. Along with planetary nebulae, open clusters are favorite objects to study the time evolution of abundance gradients, as they comprise a wide age bracket and have relatively well determined ages, based on a detailed comparison of theoretical isochrones and color magnitude diagrams (see for example Friel 1999 and Phelps 2000 for recent reviews). The distances are also generally well determined, while the stellar metallicities, mostly derived by photometric techniques, are not as accurate as in the case of some elements in photoionized nebulae, but nevertheless the gradients can be derived within a similar uncertainty, roughly 0.01 dex/kpc.

2. O/H gradients from planetary nebulae

An estimate of the time variation of the O/H radial gradient in the galactic disk has recently been made by Maciel et al. (2003). From the observed O/H abundances in a large sample of nebulae, the [Fe/H] metallicity was determined on the basis of a correlation derived for disk stars. An age-metallicity relation was used to estimate the ages of the progenitor stars, so that the temporal behaviour of the gradients could be derived. Two cases were considered (A and B), in which the sample was divided into three age groups, namely, Case A: Group I, with ages in

the range $0 < \tau$ (Gyr) < 3, Group II, for which $3 < \tau < 6$, and Group III, with $\tau > 6$ Gyr; and Case B: Group I, with ages in the range $0 < \tau < 4$, Group II, for which $4 < \tau < 5$, and Group III, with $\tau > 5$ Gyr. The O/H gradients (dex/kpc) derived by Maciel et al. (2003) are shown in the third column of Table 1. Typical uncertainties of these gradients are of the order of 0.01 dex/kpc. For details on the determination of the gradients the reader is referred to the original paper. It can be seen that the O/H gradient flattens out from the older groups to the younger ones, which is especially true for Case B, in which the groups were chosen to have approximately the same number of objects. Although the choice of the age groups is arbitrary, in all cases the flattening of the gradient is apparent. As discussed by Maciel et al. (2003), even though the absolute ages may be in error, it is unlikely that the relative ages are incorrect, so that the flattening of the gradient, although small, is probably real. In addition, Maciel et al. (2003) performed an independent calculation of the ages, on the basis of a relationship between the N/O abundance and the progenitor star mass, which led to the original stellar mass on the main sequence and therefore to another estimate of the age, with results similar to those shown in Table 1.

Table 1 Abundance gradients: planetary nebulae

Group	Age (Gyr)	$d\log(\text{O/H})/dR$	$d[\text{Fe/H}]/dR$
Case A			
I	$0 - 3$	-0.065	-0.079
II	$3 - 6$	-0.072	-0.087
III	> 6	-0.116	-0.141
Case B			
I	$0 - 5$	-0.047	-0.057
II	$4 - 5$	-0.089	-0.108
III	> 5	-0.094	-0.114

3. [Fe/H] gradients from open clusters

As mentioned in the Introduction, open clusters are favorite objects for which the determination of abundance gradients is possible (see for example Friel 1995, 1999, and Phelps 2000 for recent reviews). Recently, new catalogues of open clusters have

become available, which include space and kinematical data, as well as metallicities and estimates of the ages. In the work by Chen et al. (2003), which is based on the catalogue by Dias et al. (2002), a total of 119 clusters have been assembled for which distances and metallicities are available, which led to an average gradient of $d[\text{Fe/H}]/dR \simeq -0.063$ dex/kpc for the whole sample. This value is in good agreement with the average gradient of -0.06 dex/kpc obtained by Friel et al. (2002), based on an updated abundance calibration of spectroscopic indices in a sample containing 459 stars in 39 clusters. Taking into account two different age groups (ages < 0.8 Gyr and ≥ 0.8 Gyr, respectively), Chen et al. (2003) concluded that the iron gradient was steeper in the past, in agreement with the results derived from O/H abundances in planetary nebulae. The conclusion by Chen et al. (2003) on the time variation of the gradients confirms the earlier one by Friel et al. (2002), which is extremely important, as they have largely used different samples with similar results, so that the effect of a possible non- homogeneity of the samples is probably small.

Table 2 - Abundance gradients: open clusters

Group	Age (Gyr)	$d[\text{Fe/H}]/dR$	n	r
Case A				
I	≤ 0.8	-0.024	80	-0.22
II	> 0.8	-0.075	38	-0.70
Case B				
I	≤ 0.8	-0.024	80	-0.22
II	$0.8 - 2.0$	-0.067	18	-0.69
III	> 2.0	-0.084	20	-0.71

In order to obtain a more accurate comparison between the [Fe/H] gradients from open clusters and the planetary nebula data, we have used the sample by Chen et al. (2003) and considered two different cases, namely: Case A, with two age groups, and Case B, with 3 age groups, as defined in Table 2. We have assumed $R_0 = 7.6$ kpc for the distance of the LSR to the galactic center, as in Maciel et al. (2003), but the results are essentially unchanged if $R_0 = 8.0$ kpc or $R_0 = 8.5$ kpc. We have restricted our analysis to galactocentric distances $R < 16$ kpc, and excluded the object Berkeley 29, which does not satisfy this criterium (see Chen et al. 2003 for details). The total number of clusters in the sample is then 118. The

derived [Fe/H] gradients (dex/kpc), the number of objects in each group (n) and the correlation coefficent (r) are shown in columns 3 to 5 of Table 2. The derived uncertainties in the gradients are in the range 0.01 to 0.02 dex/kpc. All age groups have galactocentric distances roughly in the range $R \simeq 6$ to 15 kpc, so that the derived gradients are representative of the galactic disk. There is some tendency for the clusters located at $R < 8$ kpc to be young, reflecting the fact that older clusters are probably destroyed by collisions with molecular clouds in the inner Galaxy.

4. Discussion

An analysis of the O/H gradients from planetary nebulae shown in Table 1 and the [Fe/H] gradients from open clusters (Table 2) confirm that the average gradients are flattening out for the last 8 Gyr approximately, as suggested by Chen et al. (2003). We can improve on this conclusion by converting the O/H gradient into a [Fe/H] gradient, so that both sources of data can be directly compared. In fact, the O/H and [Fe/H] are supposed to be similar, but not exactly equal, which can be concluded by an inspection of the relation between the [O/Fe] ratio and the metallicity [Fe/H] in the galactic disk.

[Fe/H] gradients cannot be determined directly from planetary nebulae, as the iron lines are weak and a sizable fraction of this element is probably locked up in grains. However, a relation between the iron and oxygen abundances can be derived from observed properties of the stellar populations in the galactic disk. A detailed discussion on the metallicities and radial gradients from a variety of sources such as HII regions, hot stars and planetary nebulae in the galactic disk has been recently presented by Maciel (2002). According to this analysis, an independent [O/Fe] $\times$ [Fe/H] relation has been obtained for the galactic disk, from which we can write approximately

$$[\text{Fe/H}] = \gamma + \delta \ (\log \text{O/H} + 12), \tag{1}$$

where $\gamma \simeq -10.841$ and $\delta \simeq 1.214$. Here it has been implicitely assumed that $\log(\text{O/H})_\odot + 12 = 8.83$ (Grevesse & Sauval 1998). Note that Maciel et al. (2003) used a slightly larger value for the solar neighbourhood, $\delta \simeq 1.4$, but the main conclusions of the present paper are not affected by this discrepancy. Since both O/H and [Fe/H] gradients are assumed to be linear, it is easy to see that

$$d[\text{Fe/H}]/dR \simeq \delta \ d \log \ (\text{O/H})/dR, \tag{2}$$

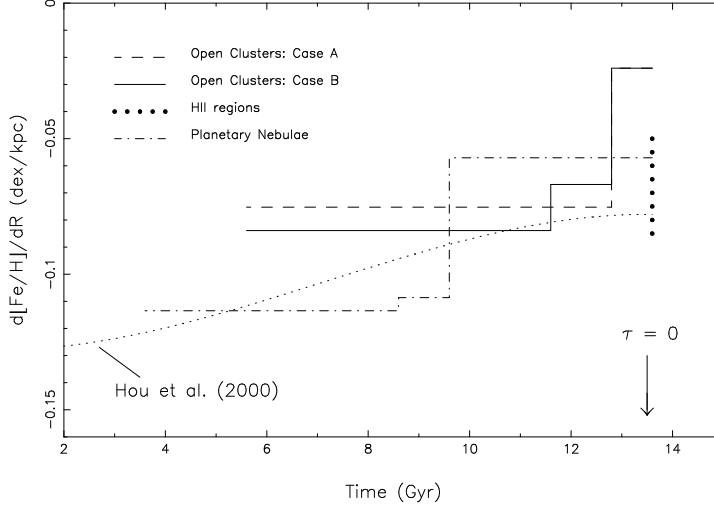which can be applied to the O/H gradients of Table 1. The derived [Fe/H] gradients are given in the last column of Table 1.

Figure 1. Time variation of the [Fe/H] abundance gradient (dex/kpc). The age of the galactic disk is assumed to be 13.5 Gyr. The open cluster gradients are as follows: Case A (dashed line) and Case B (solid line). The converted [Fe/H] gradients for the planetary nebulae are shown by the dot-and-dashed lines, corresponding to Case B of Maciel et al. (2003). The solid dots at the present time ($\tau = 0$) show the average gradients of HII regions, converted to [Fe/H] gradients as in the case of the planetary nebulae. The dotted curve represents the time evolution of the [Fe/H] gradient according to the theoretical models of Hou et al. (2000).

The results are better seen in Figure 1, where we plot the [Fe/H] gradients from the open clusters in Case A (dashed line) and Case B (solid line). The corrected planetary nebula [Fe/H] gradients (dot-and-dashed line) are shown for Case B only, which is more realistic, as discussed by Maciel et al. (2003). The average HII region gradients, converted to [Fe/H] gradients as in the case of the planetary nebulae, are shown as solid dots at $\tau \simeq 0$.

We have also included for comparison purposes the time evolution of the [Fe/H] gradient predicted by Hou et al. (2000), which is based on an inside-out scenario for the formation of the disk using metallicity dependent yields (dotted curve).

It can be seen both from Figure 1 and Tables 1 and 2 that the open cluster gradients agree very well with the gradients derived from planetary nebulae, in the sense that both indicate a time flattening of the gradients during the lifetimes of these objects. The observational data also show a good agreement with theoretical models by Hou et al. (2000), as indicated by the dotted curve in Figure 1. This conclusion holds in spite of the relatively large uncertainty involved in the age determinations, especially in the case of the planetary nebula progenitor stars.

6

Although the division of the open clusters into different age groups is arbitrary, it can be seen that the time variation of the gradients is not sensitive to the particular groups chosen. In fact, as long as the age groups contain a reasonably large fraction of the total sample, the precise definition of the groups is rather irrelevant.

It can also be seen that the application of a correction factor to the O/H gradient as given by the δ parameter given above leads to a better agreement between both sources of data. The flattening rate is still uncertain, but from a comparison of both samples an average rate of about 0.005 dex kpc^{-1} Gyr^{-1} can be obtained, which is similar to the earlier results by Maciel et al. (2003) and Chen et al. (2003). Although this value is still uncertain, it clearly sets the order of magnitude of the time flattening of the gradients, at least for the time interval of roughly 10 Myr to 5 Gyr, for which our samples are reasonably well defined. The gradient of about -0.07 dex/kpc derived for cepheid variables (Andrievsky et al. 2002) also supports this conclusion, adopting ages in the range 20–300 Myr for these objects. A steeper rate at $\tau > 5$ Gyr cannot be ruled out, in view of the results for the planetary nebulae of group III. Regarding the most recent epochs, $\tau < 10$ Myr, assuming that the HII region gradient is representative of the present time, the planetary nebula data and the HII region results suggest a continuous flattening in the last few Myr. Taking into account the open clusters of Group I, there is apparently some steepening in the recent epoch, but it should be mentioned that most of the clusters in this group are located at $R < 10$ kpc, while the other groups are more evenly distributed in the galactic disk. Therefore, the derived gradient of Group I may in fact be a lower limit, which is supported by the lower correlation coefficient shown in Table 2. Clearly, more data is necessary to settle the fine points of this question.

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